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Activity Report 2018

Project-Team ACUMES

Analysis and Control of Unsteady Models for Engineering Sciences

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Numerical schemes and simulations

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2. Overall Objectives

2.1. Overall Objectives

ACUMES aims at developing a rigorous framework for numerical simulations and optimal control for transportation and buildings, with focus on multi-scale, heterogeneous, unsteady phenomena subject to uncertainty. Starting from established macroscopic Partial Differential Equation (PDE) models, we pursue a set of innovative approaches to include small-scale phenomena, which impact the whole system. Targeting applications contributing to sustainability of urban environments, we couple the resulting models with robust control and optimization techniques.

Modern engineering sciences make an important use of mathematical models and numerical simulations at the conception stage. Effective models and efficient numerical tools allow for optimization before production and to avoid the construction of expensive prototypes or costly post-process adjustments. Most up-to-date modeling techniques aim at helping engineers to increase performances and safety and reduce costs and pollutant emissions of their products. For example, mathematical traffic flow models are used by civil engineers to test new management strategies in order to reduce congestion on the existing road networks and improve crowd evacuation from buildings or other confined spaces without constructing new infrastructures. Similar models are also used in mechanical engineering, in conjunction with concurrent optimization methods, to reduce energy consumption, noise and pollutant emissions of cars, or to increase thermal and structural efficiency of buildings while, in both cases, reducing ecological costs.

Nevertheless, current models and numerical methods exhibit some limitations:

- Most simulation-based design procedures used in engineering still rely on steady (time-averaged) state models. Significant improvements have already been obtained with such a modeling level, for instance by optimizing car shapes, but finer models taking into account unsteady phenomena are required in the design phase for further improvements.
- The classical purely macroscopic approach, while offering a framework with a sound analytical basis, performing numerical techniques and good modeling features to some extent, is not able to reproduce some particular phenomena related to specific interactions occurring at lower (possibly micro) level. We refer for example to self-organizing phenomena observed in pedestrian flows, or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere. These flow characteristics need to be taken into account to obtain more precise models and improved optimal solutions.
- Uncertainty related to operational conditions (e.g. inflow velocity in aerodynamics), or models (e.g. individual behavior in crowds) is still rarely considered in engineering analysis and design, yielding solutions of poor robustness.

This project focuses on the analysis and optimal control of classical and non-classical evolutionary systems of Partial Differential Equations (PDEs) arising in the modeling and optimization of engineering problems related to safety and sustainability of urban environments, mostly involving fluid-dynamics and structural mechanics. The complexity of the involved dynamical systems is expressed by multi-scale, time-dependent phenomena, possibly subject to uncertainty, which can hardly be tackled using classical approaches, and require the development of unconventional techniques.

3. Research Program

3.1. Research directions

The project develops along the following two axes:

- modeling complex systems through novel (unconventional) PDE systems, accounting for multi-scale phenomena and uncertainty;
- optimization and optimal control algorithms for systems governed by the above PDE systems.

These themes are motivated by the specific problems treated in the applications, and represent important and up-to-date issues in engineering sciences. For example, improving the design of transportation means and civil buildings, and the control of traffic flows, would result not only in better performances of the object of the optimization strategy (vehicles, buildings or road networks level of service), but also in enhanced safety and lower energy consumption, contributing to reduce costs and pollutant emissions.

3.1.1. PDE models accounting for multi-scale phenomena and uncertainties

Dynamical models consisting of evolutionary PDEs, mainly of hyperbolic type, appear classically in the applications studied by the previous Project-Team Opale (compressible flows, traffic, cell-dynamics, medicine, etc). Yet, the classical purely macroscopic approach is not able to account for some particular phenomena related to specific interactions occurring at smaller scales. These phenomena can be of greater importance when dealing with particular applications, where the "first order" approximation given by the purely macroscopic approach reveals to be inadequate. We refer for example to self-organizing phenomena observed in pedestrian flows [115], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [143].

Nevertheless, macroscopic models offer well known advantages, namely a sound analytical framework, fast numerical schemes, the presence of a low number of parameters to be calibrated, and efficient optimization procedures. Therefore, we are convinced of the interest of keeping this point of view as dominant, while completing the models with information on the dynamics at the small scale / microscopic level. This can be achieved through several techniques, like hybrid models, homogenization, mean field games. In this project, we will focus on the aspects detailed below.

The development of adapted and efficient numerical schemes is a mandatory completion, and sometimes ingredient, of all the approaches listed below. The numerical schemes developed by the team are based on finite volumes or finite elements techniques, and constitute an important tool in the study of the considered models, providing a necessary step towards the design and implementation of the corresponding optimization algorithms, see Section 3.1.2.

3.1.1.1. Micro-macro couplings

Modeling of complex problems with a dominant macroscopic point of view often requires couplings with small scale descriptions. Accounting for systems heterogeneity or different degrees of accuracy usually leads to coupled PDE-ODE systems.

In the case of heterogeneous problems the coupling is "intrinsic", i.e. the two models evolve together and mutually affect each-other. For example, accounting for the impact of a large and slow vehicle (like a bus or a truck) on traffic flow leads to a strongly coupled system consisting of a (system of) conservation law(s) coupled with an ODE describing the bus trajectory, which acts as a moving bottleneck.The coupling is realized through a local unilateral moving constraint on the flow at the bus location, see [84] for an existence result and [68], [83] for numerical schemes.

If the coupling is intended to offer higher degree of accuracy at some locations, a macroscopic and a microscopic model are connected through an artificial boundary, and exchange information across it through suitable boundary conditions. See [74], [103] for some applications in traffic flow modelling, and [94], [99], [101] for applications to cell dynamics.

The corresponding numerical schemes are usually based on classical finite volume or finite element methods for the PDE, and Euler or Runge-Kutta schemes for the ODE, coupled in order to take into account the interaction fronts. In particular, the dynamics of the coupling boundaries require an accurate handling capturing the possible presence of non-classical shocks and preventing diffusion, which could produce wrong solutions, see for example [68], [83].

We plan to pursue our activity in this framework, also extending the above mentioned approaches to problems in two or higher space dimensions, to cover applications to crowd dynamics or fluid-structure interaction.

3.1.1.2. Micro-macro limits

Rigorous derivation of macroscopic models from microscopic ones offers a sound basis for the proposed modeling approach, and can provide alternative numerical schemes, see for example [75], [86] for the derivation of Lighthill-Whitham-Richards [126], [142] traffic flow model from Follow-the-Leader and [95] for results on crowd motion models (see also [117]). To tackle this aspect, we will rely mainly on two (interconnected) concepts: measure-valued solutions and mean-field limits.

The notion of **measure-valued solutions** for conservation laws was first introduced by DiPerna [87], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [96] and references therein. Measure-valued functions have been recently advocated as the appropriate notion of solution to tackle problems for which analytical results (such as existence and uniqueness of weak solutions in distributional sense) and numerical convergence are missing [57], [98]. We refer, for example, to the notion of solution for non-hyperbolic systems [105], for which no general theoretical result is available at present, and to the convergence of finite volume schemes for systems of hyperbolic conservation laws in several space dimensions, see [98].

In this framework, we plan to investigate and make use of measure-based PDE models for vehicular and pedestrian traffic flows. Indeed, a modeling approach based on (multi-scale) time-evolving measures (expressing the agents probability distribution in space) has been recently introduced (see the monograph [79]), and proved to be successful for studying emerging self-organised flow patterns [78]. The theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures of mean field type [106], where one lets the number of agents going to infinity, while keeping the total mass constant. In this case, one must prove that the *empirical measure*, corresponding to the sum of Dirac measures concentrated at the agents positions, converges to a measure-valued solution of the corresponding macroscopic evolution equation. We recall that a key ingredient in this approach is the use of the *Wasserstein distances* [151], [152]. Indeed, as observed in [135], the usual L^1 spaces are not natural in this context, since they don't guarantee uniqueness of solutions.

This procedure can potentially be extended to more complex configurations, like for example road networks or different classes of interacting agents, or to other application domains, like cell-dynamics.

Another powerful tool we shall consider to deal with micro-macro limits is the so-called **Mean Field Games (MFG)** technique (see the seminal paper [125]). This approach has been recently applied to some of the systems studied by the team, such as traffic flow and cell dynamics. In the context of crowd dynamics, including the case of several populations with different targets, the mean field game approach has been adopted in [64], [65], [88], [124], under the assumption that the individual behavior evolves according to a stochastic process, which gives rise to parabolic equations greatly simplifying the analysis of the system. Besides, a deterministic context is studied in [138], which considers a non-local velocity field. For cell dynamics, in order to take into account the fast processes that occur in the migration-related machinery, a framework such the one developed in [82] to handle games "where agents evolve their strategies according to the best-reply scheme on a much faster time scale than their social configuration variables" may turn out to be suitable. An alternative framework to MFG is also considered. This framework is based on the formulation of -Nash- games constrained by the **Fokker-Planck** (FP, [53]) partial differential equations that govern the time evolution of the probability density functions -PDF- of stochastic systems and on objectives that may require to follow a given PDF trajectory or to minimize an expectation functional.

3.1.1.3. Non-local flows

Non-local interactions can be described through macroscopic models based on integro-differential equations. Systems of the type

$$\partial_t u + \text{div}_{\mathbf{x}} F(t, \mathbf{x}, u, W) = 0, \qquad t > 0, \ \mathbf{x} \in \mathbb{R}^d, \ d \geq 1, \tag{1}$$

where $u = u(t, \mathbf{x}) \in \mathbb{R}^N$, $N \geq 1$ is the vector of conserved quantities and the variable $W = W(t, x, u)$ depends on an integral evaluation of u, arise in a variety of physical applications. Space-integral terms are considered for example in models for granular flows [50], sedimentation [59], supply chains [109], conveyor belts [110], biological applications like structured populations dynamics [134], or more general problems like gradient constrained equations [51]. Also, non-local in time terms arise in conservation laws with memory, starting from [81]. In particular, equations with non-local flux have been recently introduced in traffic flow modeling to account for the reaction of drivers or pedestrians to the surrounding density of other individuals, see [60], [67], [71], [107], [146]. While pedestrians are likely to react to the presence of people all around them, drivers will mainly adapt their velocity to the downstream traffic, assigning a greater importance to closer vehicles. In particular, and in contrast to classical (without integral terms) macroscopic equations, these models are able to display finite acceleration of vehicles through Lipschitz bounds on the mean velocity [60], [107] and lane formation in crossing pedestrian flows.

General analytical results on non-local conservation laws, proving existence and eventually uniqueness of solutions of the Cauchy problem for (1), can be found in [52] for scalar equations in one space dimension ($N = d = 1$), in [72] for scalar equations in several space dimensions ($N = 1$, $d \geq 1$) and in [46], [73], [77] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [46], [107] and [123].

Relying on these encouraging results, we aim to push a step further the analytical and numerical study of non-local models of type (1), in particular concerning well-posedness of initial - regularity of solutions, boundary value problems and high-order numerical schemes.

3.1.1.4. Uncertainty in parameters and initial-boundary data

Different sources of uncertainty can be identified in PDE models, related to the fact that the problem of interest is not perfectly known. At first, initial and boundary condition values can be uncertain. For instance, in traffic flows, the time-dependent value of inlet and outlet fluxes, as well as the initial distribution of vehicles density, are not perfectly determined [66]. In aerodynamics, inflow conditions like velocity modulus and direction, are subject to fluctuations [113], [133]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some details [90]. Another source of uncertainty is related to the value of some parameters in the PDE models. This is typically the case of parameters in turbulence models in fluid mechanics, which have been calibrated according to some reference flows but are not universal [144], [150], or in traffic flow models, which may depend on the type of road, weather conditions, or even the country of interest (due to differences in driving rules and conductors behaviour). This leads to equations with flux functions depending on random parameters [145], [148], for which the mean and the variance of the solutions can be computed using different techniques. Indeed, uncertainty quantification for systems governed by PDEs has become a very active research topic in the last years. Most approaches are embedded in a probabilistic framework and aim at quantifying statistical moments of the PDE solutions, under the assumption that the characteristics of uncertain parameters are known. Note that classical Monte-Carlo approaches exhibit low convergence rate and consequently accurate simulations require huge computational times. In this respect, some enhanced algorithms have been proposed, for example in the balance law framework [131]. Different approaches propose to modify the PDE solvers to account for this probabilistic context, for instance by defining the non-deterministic part of the solution on an orthogonal basis (Polynomial Chaos decomposition) and using a Galerkin projection [113], [122], [127], [154] or an entropy closure method [85], or by discretizing the probability space and extending the numerical schemes to the stochastic components [45]. Alternatively, some other approaches maintain a fully deterministic PDE resolution, but approximate the solution in the vicinity of the reference parameter values by Taylor series expansions based on first- or second-order sensitivities [139], [150], [153].

Our objective regarding this topic is twofold. In a pure modeling perspective, we aim at including uncertainty quantification in models calibration and validation for predictive use. In this case, the choice of the techniques will depend on the specific problem considered [58]. Besides, we plan to extend previous works on sensitivity analysis [90], [128] to more complex and more demanding problems. In particular, high-order Taylor expansions of the solution (greater than two) will be considered in the framework of the Sensitivity Equation Method [61] (SEM) for unsteady aerodynamic applications, to improve the accuracy of mean and variance estimations. A second targeted topic in this context is the study of the uncertainty related to turbulence closure parameters, in the sequel of [150]. We aim at exploring the capability of the SEM approach to detect a change of flow topology, in case of detached flows. Our ambition is to contribute to the emergence of a new generation of simulation tools, which will provide solution densities rather than values, to tackle real-life uncertain problems. This task will also include a reflection about numerical schemes used to solve PDE systems, in the perspective of constructing a unified numerical framework able to account for exact geometries (isogeometric methods), uncertainty propagation and sensitivity analysis w.r.t. control parameters.

3.1.2. Optimization and control algorithms for systems governed by PDEs

The non-classical models described above are developed in the perspective of design improvement for real-life applications. Therefore, control and optimization algorithms are also developed in conjunction with these models. The focus here is on the methodological development and analysis of optimization algorithms for PDE systems in general, keeping in mind the application domains in the way the problems are mathematically formulated.

3.1.2.1. Sensitivity VS adjoint equation

Adjoint methods (achieved at continuous or discrete level) are now commonly used in industry for steady PDE problems. Our recent developments [141] have shown that the (discrete) adjoint method can be efficiently applied to cost gradient computations for time-evolving traffic flow on networks, thanks to the special structure of the associated linear systems and the underlying one dimensionality of the problem. However, this strategy is questionable for more complex (e.g. 2D/3D) unsteady problems, because it requires sophisticated and time-consuming check-pointing and/or re-computing strategies [56], [108] for the backward time integration of the adjoint variables. The sensitivity equation method (SEM) offers a promising alternative [89], [118], if the number of design parameters is moderate. Moreover, this approach can be employed for other goals, like fast evaluation of neighboring solutions or uncertainty propagation [90].
Regarding this topic, we intend to apply the continuous sensitivity equation method to challenging problems. In particular, in aerodynamics, multi-scale turbulence models like Large-Eddy Simulation (LES) [143] , Detached-Eddy Simulation (DES) [147] or Organized-Eddy Simulation (OES) [62], are more and more employed to analyse the unsteady dynamics of the flows around bluff-bodies, because they have the ability to compute the interactions of vortices at different scales, contrary to classical Reynolds-Averaged Navier-Stokes models. However, their use in design optimization is tedious, due to the long time integration required. In collaboration with turbulence specialists (M. Braza, CNRS - IMFT), we aim at developing numerical methods for effective sensitivity analysis in this context, and apply them to realistic problems, like the optimization of active flow control devices. Note that the use of SEM allows computing cost functional gradients at any time, which permits to construct new gradient-based optimization strategies like instantaneous-feedback method [120] or multiobjective optimization algorithm (see section below).

3.1.2.2. Multi-objective descent algorithms for multi-disciplinary, multi-point, unsteady optimization or robust-design

n differentiable optimization, multi-disciplinary, multi-point, unsteady optimization or robust-design can all be formulated as multi-objective optimization problems. In this area, we have proposed the *Multiple-Gradient Descent Algorithm (MGDA)* to handle all criteria concurrently [91] [92]. Originally, we have stated a principle according which, given a family of local gradients, a descent direction common to all considered objective-functions simultaneously is identified, assuming the Pareto-stationarity condition is not satisfied. When the family is linearly-independent, we dispose of a direct algorithm. Inversely, when the family is linearly-dependent, a quadratic-programming problem should be solved. Hence, the technical difficulty is mostly conditioned by the number m of objective functions relative to the search space dimension n. In this respect, the basic algorithm has recently been revised [93] to handle the case where $m > n$, and even $m \gg n$, and is currently being tested on a test-case of robust design subject to a periodic time-dependent Navier-Stokes flow.

The multi-point situation is very similar and, being of great importance for engineering applications, will be treated at large.

Moreover, we intend to develop and test a new methodology for robust design that will include uncertainty effects. More precisely, we propose to employ MGDA to achieve an effective improvement of all criteria simultaneously, which can be of statistical nature or discrete functional values evaluated in confidence intervals of parameters. Some recent results obtained at ONERA [136] by a stochastic variant of our methodology confirm the viability of the approach. A PhD thesis has also been launched at ONERA/DADS.

Lastly, we note that in situations where gradients are difficult to evaluate, the method can be assisted by a meta-model [156].

3.1.2.3. Bayesian Optimization algorithms for efficient computation of general equilibria

Bayesian Optimization -BO- relies on Gaussian processes, which are used as emulators (or surrogates) of the black-box model outputs based on a small set of model evaluations. Posterior distributions provided by the Gaussian process are used to design acquisition functions that guide sequential search strategies that balance between exploration and exploitation. Such approaches have been transposed to frameworks other than optimization, such as uncertainty quantification. Our aim is to investigate how the BO apparatus can be applied to the search of general game equilibria, and in particular the classical Nash equilibrium (NE). To this end, we propose two complementary acquisition functions, one based on a greedy search approach and one based on the Stepwise Uncertainty Reduction paradigm [100]. Our proposal is designed to tackle derivative-free, expensive models, hence requiring very few model evaluations to converge to the solution.

3.1.2.4. Decentralized strategies for inverse problems

Most if not all the mathematical formulations of inverse problems (a.k.a. reconstruction, identification, data recovery, non destructive engineering,...) are known to be ill posed in the Hadamard sense. Indeed, in general, inverse problems try to fulfill (minimize) two or more very antagonistic criteria. One classical example is the Tikhonov regularization, trying to find artificially smoothed solutions close to naturally non-smooth data.

We consider here the theoretical general framework of parameter identification coupled to (missing) data recovery. Our aim is to design, study and implement algorithms derived within a game theoretic framework, which are able to find, with computational efficiency, equilibria between the "identification related players" and the "data recovery players". These two parts are known to pose many challenges, from a theoretical point of view, like the identifiability issue, and from a numerical one, like convergence, stability and robustness problems. These questions are tricky [47] and still completely open for systems like e.g. coupled heat and thermoelastic joint data and material detection.

4. Application Domains

4.1. Active flow control for vehicles

The reduction of CO2 emissions represents a great challenge for the automotive and aeronautic industries, which committed respectively a decrease of 20% for 2020 and 75% for 2050. This goal will not be reachable, unless a significant improvement of the aerodynamic performance of cars and aircrafts is achieved (e.g. aerodynamic resistance represents 70% of energy losses for cars above 90 km/h). Since vehicle design cannot be significantly modified, due to marketing or structural reasons, active flow control technologies are one of the most promising approaches to improve aerodynamic performance. This consists in introducing micro-devices, like pulsating jets or vibrating membranes, that can modify vortices generated by vehicles. Thanks to flow non-linearities, a small energy expense for actuation can significantly reduce energy losses. The efficiency of this approach has been demonstrated, experimentally as well as numerically, for simple configurations [155]. However, the lack of efficient and flexible numerical models, that allow to simulate and optimize a large number of such devices on realistic configurations, is still a bottleneck for the emergence of this technology in an industrial context. In particular, the prediction of actuated flows requires the use of advanced turbulence closures, like Detached Eddy Simulation or Large Eddy Simulation [104]. They are intrinsically three-dimensional and unsteady, yielding a huge computational effort for each analysis, which makes their use tedious for optimization purpose. In this context, we intend to contribute to the following research axes:

- *Sensitivity analysis for actuated flows.* Adjoint-based (reverse) approaches, classically employed in design optimization procedure to compute functional gradients, are not well suited to this context. Therefore, we propose to explore the alternative (direct) formulation, which is not so much used, in the perspective of a better characterization of actuated flows and optimization of control devices.
- *Hierarchical optimization of control devices.* The optimization of dozen of actuators, in terms of locations, frequencies, amplitudes, will be practically tractable only if a hierarchical approach is adopted, which mixes fine (DES) and coarse (URANS) simulations, and possibly experiments. We intend to develop such an optimization strategy on the basis of Gaussian Process models (*multi-fidelity kriging*).

4.2. Vehicular and pedestrian traffic flows

Intelligent Transportation Systems (ITS) is nowadays a booming sector, where the contribution of mathematical modeling and optimization is widely recognized. In this perspective, traffic flow models are a commonly cited example of "complex systems", in which individual behavior and self-organization phenomena must be taken into account to obtain a realistic description of the observed macroscopic dynamics [114]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [63] and references therein. In particular, we will focus on the following aspects:

- *Junction models.* We are interested in designing a general junction model both satisfying basic analytical properties guaranteeing well-posedness and being realistic for traffic applications. In particular, the model should be able to overcome severe drawbacks of existing models, such as restrictions on the number of involved roads and prescribed split ratios [76], [102], which limit their applicability to real world situations. Hamilton-Jacobi equations could be also an interesting direction of research, following the recent results obtained in [119].
- *Data assimilation.* In traffic flow modeling, the capability of correctly estimating and predicting the state of the system depends on the availability of rich and accurate data on the network. Up to now, the most classical sensors are fixed ones. They are composed of inductive loops (electrical wires) that are installed at different spatial positions of the network and that can measure the traffic flow, the occupancy rate (i.e. the proportion of time during which a vehicle is detected to be over the loop) and the speed (in case of a system of two distant loops). These data are useful / essential to calibrate the phenomenological relationship between flow and density which is known in the traffic literature as the Fundamental Diagram. Nowadays, thanks to the wide development of mobile internet and geolocalization techniques and its increasing adoption by the road users, smartphones have turned into perfect mobile sensors in many domains, including in traffic flow management. They can provide the research community with a large database of individual trajectory sets that are known as Floating Car Data (FCD), see [116] for a real field experiment. Classical macroscopic models, say (hyperbolic systems of) conservation laws, are not designed to take into account this new kind of microscopic data. Other formulations, like Hamilton-Jacobi partial differential equations, are most suited and have been intensively studied in the past five years (see [69], [70]), with a stress on the (fixed) Eulerian framework. Up to our knowledge, there exist a few studies in the time-Lagrangian as well as space-Lagrangian frameworks, where data coming from mobile sensors could be easily assimilated, due to the fact that the Lagrangian coordinate (say the label of a vehicle) is fixed.

- *Control of autonomous vehicles.* Traffic flow is usually controlled via traffic lights or variable speed limits, which have fixed space locations. The deployment of autonomous vehicles opens new perspectives in traffic management, as the use of a small fraction of cars to optimize the overall traffic. In this perspective, the possibility to track vehicles trajectories either by coupled micro-macro models [84], [103] or via the Hamilton-Jacobi approach [69], [70] could allow to optimize the flow by controlling some specific vehicles corresponding to internal conditions.

4.3. Virtual Fractional Flow Reserve in Coronary stenting

Atherosclerosis is a chronic inflammatory disease that affects the entire arterial network and especially the coronary arteries. It is an accumulation of lipids over the arterial surface due to a dysfunction of this latter. The objective of clinical intervention, in this case, is to establish a revascularization using different angioplasty techniques, among which the implantation of stents is the most widespread. This intervention involves introducing a stent into the damaged portion in order to allow the blood to circulate in a normal way over all the vessels. Revascularization is based on the principle of remedying ischemia, which is a decrease or an interruption of the supply of oxygen to the various organs. This anomaly is attenuated by the presence of several lesions (multivessel disease patients), which can lead to several complications. The key of a good medical intervention is the fact of establishing a good diagnosis, in order to decide which lesion requires to be treated. In the diagnosis phase, the clinician uses several techniques, among which angiography is the most popular. Angiography is an X-ray technique to show the inside (the lumen) of blood vessels, in order to identify vessel narrowing: stenosis. Despite its widespread use, angiography is often imperfect in determining the physiological significance of coronary stenosis. If the problem remains simple for non significant lesions ($\leq 40\%$) or very severe ($\geq 70\%$), a very important category of intermediate lesions must benefit from a functional evaluation which will determine the strategy of treatment [80].

The technique of the fractional flow reserve FFR has derived from the initial coronary physical approaches decades ago. Since then, many studies have demonstrated its effectiveness in improving the patients prognosis, by applying the appropriate approach. Its contribution in the reduction of mortality was statistically proved by the FAME (Fractional Flow Reserve Versus Angiography for Multivessel Evaluation) study [158]. It is established that the FFR can be easily measured during coronary angiography by calculating the ratio of distal coronary pressure P_d to aortic pressure P_a. These pressures are measured simultaneously with a special guide-wire. FFR in a normal coronary artery equals to 1.0. FFR value of 0.80 or less identifies ischemia-causing coronary lesions with an accuracy of more than 90% [158].

Obviously, from an interventional point of view, the FFR is binding since it is invasive. It should also be noted that this technique induces additional costs, which are not covered by insurances in several countries. For these reasons, it is used only in less than 10% of the cases.

In this perspective, a new virtual version of the FFR, entitled VFFR, has emerged as an attractive and non-invasive alternative to standard FFR, see [149], [132]. VFFR is based on computational modeling, mainly fluid and fluid-structural dynamics. However, there are key scientific, logistic and commercial challenges that need to be overcome before VFFR can be translated into routine clinical practice.

While most of the studies related to vFFR use Navier-Stokes models, we focus on the non-newtonian case, starting with a generalized fluid flow approach. These models are more relevant for the coronary arteries, and we expect that the computation of the FFR should then be more accurate. We are also leading numerical studies to assess the impact (on the FFR) of the interaction of the physical devices (catheter, optical captors, spheroids) with the blood flow.

4.4. Other application fields

Besides the above mentioned axes, which constitute the project's identity, the methodological tools described in Section have a wider range of application. We currently carry on also the following research actions, in collaboration with external partners.

- **Modeling cell dynamics.** Migration and proliferation of epithelial cell sheets are the two keystone aspects of the collective cell dynamics in most biological processes such as morphogenesis, embryogenesis, cancer and wound healing. It is then of utmost importance to understand their underlying mechanisms.

  Semilinear reaction-diffusion equations are widely used to give a phenomenological description of the temporal and spatial changes occurring within cell populations that undergo scattering (moving), spreading (expanding cell surface) and proliferation. We have followed the same methodology and contributed to assess the validity of such approaches in different settings (cell sheets [111], dorsal closure [49], actin organization [48]). However, epithelial cell-sheet movement is complex enough to undermine most of the mathematical approaches based on *locality*, that is mainly traveling wavefront-like partial differential equations. In [97] it is shown that Madin-Darby Canine Kidney (MDCK) cells extend cryptic lamellipodia to drive the migration, several rows behind the wound edge. In [137] MDCK monolayers are shown to exhibit similar non-local behavior (long range velocity fields, very active border-localized leader cells).

  Our aim is to start from a mesoscopic description of cell interaction: considering cells as independent anonymous agents, we plan to investigate the use of mathematical techniques adapted from the mean-field game theory. Otherwise, looking at them as interacting particles, we will use a multi-agent approach (at least for the actin dynamics). We intend also to consider approaches stemming from compartment-based simulation in the spirit of those developed in [94], [99], [101].

- **Game strategies for thermoelastography.** Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [130]. Indeed, it is well known that most pathological changes are associated with changes in tissue stiffness, while remaining isoechoic, and hence difficult to detect by ultrasound techniques. Based on elastic waves and heat flux reconstruction, thermoelastography shows no destructive or aggressive medical sequel, unlike X-ray and comparables techniques, making it a potentially prominent choice for patients.

  Physical principles of thermoelastography originally rely on dynamical structural responses of tissues, but as a first approach, we only consider static responses of linear elastic structures.
  The mathematical formulation of the thermoelasticity reconstruction is based on data completion and material identification, making it a harsh ill posed inverse problem. In previous works [112], [121], we have demonstrated that Nash game approaches are efficient to tackle ill-posedness. We intend to extend the results obtained for Laplace equations in [112], and the algorithms developed in Section 3.1.2.4 to the following problems (of increasing difficulty):
  - Simultaneous data and parameter recovery in linear elasticity, using the so-called Kohn and Vogelius functional (ongoing work, some promising results obtained).
  - Data recovery in coupled heat-thermoelasticity systems.
  - Data recovery in linear thermoelasticity under stochastic heat flux, where the imposed flux is stochastic.
  - Data recovery in coupled heat-thermoelasticity systems under stochastic heat flux, formulated as an incomplete information Nash game.
  - Application to robust identification of cracks.

- **Constraint elimination in Quasi-Newton methods.** In single-objective differentiable optimization, Newton's method requires the specification of both gradient and Hessian. As a result, the convergence is quadratic, and Newton's method is often considered as the target reference. However, in applications to distributed systems, the functions to be minimized are usually "functionals", which depend on the optimization variables by the solution of an often complex set of PDE's, through a chain of computational procedures. Hence, the exact calculation of the full Hessian becomes a complex and costly computational endeavor.

This has fostered the development of *quasi-Newton's methods* that mimic Newton's method but use only the gradient, the Hessian being iteratively constructed by successive approximations inside the algorithm itself. Among such methods, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is well-known and commonly employed. In this method, the Hessian is corrected at each new iteration by rank-one matrices defined from several evaluations of the gradient only. The BFGS method has "super-linear convergence".

For constrained problems, certain authors have developed so-called *Riemannian BFGS*, e.g. [140], that have the desirable convergence property in constrained problems. However, in this approach, the constraints are assumed to be known formally, by explicit expressions.

In collaboration with ONERA-Meudon, we are exploring the possibility of representing constraints, in successive iterations, through local approximations of the constraint surfaces, splitting the design space locally into tangent and normal sub-spaces, and eliminating the normal coordinates through a linearization, or more generally a finite expansion, and applying the BFGS method through dependencies on the coordinates in the tangent subspace only. Preliminary experiments on the difficult Rosenbrock test-case, although in low dimensions, demonstrate the feasibility of this approach. On-going research is on theorizing this method, and testing cases of higher dimensions.

- **Multi-objective optimization for nanotechnologies.** Our team takes part in a larger collaboration with CEA/LETI (Grenoble), initiated by the Inria Project-Team Nachos, and related to the Maxwell equations. Our component in this activity relates to the optimization of nanophotonic devices, in particular with respect to the control of thermal loads. We have first identified a gradation of representative test-cases of increasing complexity:
  - infrared micro-source;
  - micro-photoacoustic cell;
  - nanophotonic device.

  These cases involve from a few geometric parameters to be optimized to a functional minimization subject to a finite-element solution involving a large number of dof's. CEA disposes of such codes, but considering the computational cost of the objective functions in the complex cases, the first part of our study is focused on the construction and validation of meta-models, typically of RBF-type. Multi-objective optimization will be carried out subsequently by MGDA, and possibly Nash games.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. Awards

Tunisian Women Mathematicians' Association (TWMA) awarded B. Yahyaoui (Acumes PhD) with the Best 2017 PhD Thesis in Applied Mathematics (October 2018).

6. New Software and Platforms

6.1. MGDA

Multiple Gradient Descent Algorithm
KEYWORDS: Descent direction - Multiple gradients - Multi-objective differentiable optimization

SCIENTIFIC DESCRIPTION: The software provides a vector d whose scalar product with each of the given gradients (or directional derivative) is positive provided a solution exists. When the gradients are linearly independent, the algorithm is direct following a Gram-Schmidt orthogonalization. Otherwise, a sub-family of the gradients is identified according to a hierarchical criterion as a basis of the spanned subspace associated with a cone that contains almost all the gradient directions. Then, one solves a quadratic programming problem formulated in this basis.

https://hal.inria.fr/hal-01139994 https://hal.inria.fr/hal-01414741
FUNCTIONAL DESCRIPTION: Concerning Chapter 1, the utilization of the platform can be made via two modes : – the interactive mode, through a web interface that facilitates the data exchange between the user and an Inria dedicated machine, – the iterative mode, in which the user downloads the object library to be included in a personal optimization software. Concerning Chapters 2 and 3, the utilizer specifies cost and constraint functions by providing procedures compatible with Fortran 90. Chapter 3 does not require the specification of gradients, but only the functions themselves that are approximated by the software by quadratic meta-models.

- Participant: Jean-Antoine Désidéri
- Contact: Jean-Antoine Désidéri
- URL: http://mgda.inria.fr

6.2. Igloo

Iso-Geometric anaLysis using discOntinuOus galerkin methods
KEYWORDS: Numerical simulations - Isogeometric analysis
SCIENTIFIC DESCRIPTION: Igloo contains numerical methods to solve partial differential equations of hyperbolic type, or convection-dominant type, using an isogeometric formulation (NURBS bases) with a discontinuous Galerkin method.
FUNCTIONAL DESCRIPTION: Igloo is composed of a set of C++ libraries and applications, which allow to simulate time-dependent physical phenomena using natively CAD-based geometry descriptions.

- Author: Régis Duvigneau
- Contact: Régis Duvigneau

6.3. BuildingSmart

BuildingSmart interactive visualization
KEYWORDS: Physical simulation - 3D rendering - 3D interaction
SCIENTIFIC DESCRIPTION: The aim of the BuildingSmart project is to develop a software environment for the simulation and interactive visualisation for the design of buildings (structural safety, thermal confort).
FUNCTIONAL DESCRIPTION: The main task of the project is to study and develop solutions dedicated to interactive visualisation of building performances (heat, structural) in relation to the Building Information Modeling BIM framework, using Occulus Rift immersion.
NEWS OF THE YEAR: Demo movies are available from Youtube (see web site)

- Participants: Régis Duvigneau, Jean-Luc Szpyrka, David Rey, Clement Welsch and Abderrahmane Habbal
- Contact: Abderrahmane Habbal
- URL: http://youtu.be/MW_gIF8hUdk

7. New Results

7.1. Macroscopic traffic flow models on networks

Participants: Guillaume Costeseque, Nikodem Dymski, Paola Goatin, Nicolas Laurent-Brouty, Shuxia Tang, Yunzhi Wu, Alexandre Bayen [UC Berkeley, CA, USA], Alexander Keimer [UC Berkeley, CA, USA], Antonella Ferrara [U Pavia, Italy], Giulia Piacentini [U Pavia, Italy].

The relaxation limit for ARZ model. The Aw-Rascle-Zhang model [55], [157] can now be considered as a classical traffic flow model. In [27], we detail the mathematical behavior of the Aw-Rascle-Zhang model with relaxation [54]. In a Lagrangian setting, we use the Wave-Front-Tracking method with splitting technique to construct a sequence of approximate solutions. We prove that this sequence admits a limit. We then show that the limit is a weak entropy solution of the relaxed system associated to a given initial datum with bounded variation. Finally, we prove that this limit converges to a weak solution of the scalar conservation law when the relaxation parameter goes to zero.

Bounded acceleration. In [29], we propose a new mathematical model accounting for the boundedness of traffic acceleration at a macroscopic scale. Our model is built on a first order macroscopic PDE model coupled with an ODE describing the trajectory of the leader of a platoon accelerating at a given constant rate. We use Wave Front Tracking techniques to construct approximate solutions to the Initial Value Problem. We present some numerical examples including the case of successive traffic signals on an arterial road and we compare the solution to our model with the solution given by the classical LWR equation in order to evaluate the impact of bounded acceleration.

Second order models with moving bottlenecks. In [25], we study the Aw-Rascle-Zhang (ARZ) model with non-conservative local point constraint on the density flux introduced in [Garavello, M., and Goatin, P. The Aw-Rascle traffic model with locally constrained flow. Journal of Mathematical Analysis and Applications 378, 2 (2011), 634-648], its motivation being, for instance, the modeling of traffic across a toll gate. We prove the existence of weak solutions under assumptions that result to be more general than those required in [Garavello, M., and Villa, S. The Cauchy problem for the Aw-Rascle-Zhang traffic model with locally constrained flow. Journal of Hyperbolic Differential Equations 14, 03 (2017), 393-414]. More precisely, we do not require that the waves of the first characteristic family have strictly negative speeds of propagation. The result is achieved by showing the convergence of a sequence of approximate solutions constructed via the wave-front tracking algorithm. The case of solutions attaining values at the vacuum is considered. We also present an explicit numerical example to describe some qualitative features of the solutions.

Traffic control by autonomous vehicles. We consider the possibility of properly controlling a moving bottleneck to improve the traffic flow. The traffic is represented by means of a macroscopic model able to take into account the interactions with the bottleneck. This latter interacts with the surrounding flow modifying the traffic density and the flow speed profiles. An optimal control problem is stated by using the speed of the moving bottleneck as control variable. Specifically, in [30] the MPC (Model Predictive Control) approach is used to get a fuel consumption reduction when the traffic is congested due to the presence of a fixed bottleneck on the highway. In addition we have demonstrated that no increase of the travel time is caused by the control application. The concept illustrated in this paper suggests a future innovative traffic control approach. Indeed the prospective of exploiting special vehicles with manipulable speed to control the traffic flow is particularly attractive given the expected increasing penetration rate of autonomous vehicles in traffic networks in future years.

Well-posedness of conservation laws on networks with finite buffers. In collaboration with A. Bayen and A. Keimer (UC Berkeley), we introduce a model capable of dealing with conservation laws on networks and the coupled boundary conditions at the junctions. To that end we introduce a buffer of fixed arbitrary size and time dependent split ratios at the junctions which represent how traffic should be routed. One of the most important and interesting property of the presented model is its capability of showing spill-back phenomena over junctions. Having defined the dynamics on the level of conservation laws we lift them up to Hamilton Jacobi equations. The corresponding formulation in terms of H-J allows us to attack the problem that boundary datum of in and out-going junctions is a function of the queue size and vice versa. We do this by defining a fixed-point problem in a proper Banach space setting and prove the existence of a solution. Thus, the problem is solved on the level of Hamilton-Jacobi equations and due to the existent theory we also obtain a solution on the level of conservation laws with boundary datum in the sense of Bardos-Leroux-Nédélec.

Altogether, the system of conservation laws – locally coupled via the boundary conditions is studied for analytical questions of well-posedness, uniqueness and existence.

Finally we detail how to use this framework on a non-trivial road network, with several intersections and finite-length links.

Minimum time boundary controls. In collaboration with A. Bayen and A. Keimer (UC Berkeley), we are investigating the minimum time control problem for traffic flow. More precisely, we seek for the inflow upstream boundary condition that drives congested traffic to free flow condition on a stretch of road in minimum time.

Big Data analysis and modeling of road Traffic. Yunzhi Wu's internship, funded by Inria under the program "Transverse Actions", was co-supervised by Acumes (P. Goatin and G. Costeseque) and Zenith (F. Masseglia and R. Akbarinia). In this project, we processed the traffic data collected by loop detectors in the Mediterranean region during 3 months in 2015 (provided by DIRMED). We aimed at finding out the characteristics of traffic data and provide a new way of traffic prediction and estimation. The method of Motif Discovery was used for abnormality detection and pattern discovery. A modified method was also used for congestion prediction. Then we use the Co-Clustering method to group the data by day and loop. The clustering results were used to do a grouped calibration of fundamental diagram.

7.2. Non-local conservation laws

Participants: Felisia Angela Chiarello, Paola Goatin, Elena Rossi, Florent Berthelin [COFFEE, Inria].

F.A. Chiarello's PhD thesis focuses on non-local conservation laws. In [22], we proved the stability of entropy weak solutions, considering smooth kernels. We obtained an estimate on the dependence of the solution with respect to the kernel function, the speed and the initial datum, applying the doubling of variables technique. We also provided some numerical simulations illustrating the dependencies above for some cost functionals derived from traffic flow applications.
In the paper [21], we proved the existence for small times of weak solutions for a class of non-local systems in one space dimension, arising in traffic modeling. We approximated the problem by a Godunov type numerical scheme and we provided uniform L^∞ and BV estimates for the sequence of approximate solutions. We showed some numerical simulations illustrating the behavior of different classes of vehicles and we analyzed two cost functionals measuring the dependence of congestion on traffic composition.
We also conducted a study on Lagrangian-Antidiffusive Remap schemes (previously proposed for classical hyperbolic systems) for the above mentioned non-local multi-class traffic flow model. The error and convergence analysis show the effectiveness of the method, which is first order, in sharply capturing shock discontinuities, and better precision with respect to other methods as Lax-Friedrichs or Godunov (even 2nd order). A journal article about these results is submitted [40].

In the setting of Florent Berthelin's secondement, we studied the regularity properties of solutions of a non-local traffic model involving a convolution product. Unlike other studies, the considered kernel is discontinuous on $\mathbb{R}$. We proved Sobolev estimates and the convergence of approximate solutions solving a viscous and regularized non-local equation. It leads to weak, $C([0,T],L^2(\mathbb{R}))$, and smooth, $W^{2,2N}([0,T]\times\mathbb{R})$, solutions for the non-local traffic model [16].

7.3. Well-posedness results for Initial Boundary Value Problems

Participants: Paola Goatin, Elena Rossi.

We focused on the IBVP for a general scalar balance law in one space dimension and proved its well-posedness and the stability of its solutions with respect to variations in the flux and in the source terms. For both results, the initial and boundary data are required to be bounded functions with bounded total variations. The existence of solutions is obtained from the convergence of a Lax-Friedrichs type algorithm, while the stability follows from an application of Kruzkov's doubling of variables method [33].

Exploiting the same techniques, we focused also on a non local version of the scalar IBVP for a conservation law. The flux is indeed assumed to depend non locally on the unknown, and the non local operator is "aware of boundaries". For this non local problem, existence and uniqueness of solutions are provided. In particular, the uniqueness follows from the Lipschitz continuous dependence on initial and boundary data, which is proved exploiting the results on the local IBVP [43].

7.4. Isogeometric analysis

Participants: Régis Duvigneau, Stefano Pezzano, Maxime Stauffert, Asma Azaouzi [ENIT], Maher Moakher [ENIT].

High-order isogeometric solvers are developed, based on CAD representations for both the geometry and the solution space, for applications targeted by the team, in particular hyperbolic or convection-dominated problems. Specifically, we investigate a Discontinuous Galerkin method for hyperbolic systems such as compressible Euler, or Navier-Stokes equations, based on an isogeometric formulation[24]: the partial differential equations governing the flow are solved on rational parametric elements, that preserve exactly the geometry of boundaries defined by Non-Uniform Rational B-Splines (NURBS) thanks to Bézier extraction techniques, while the same rational approximation space is adopted for the solution.

This topic has been studied in the context of A. Azaouzi's PhD work defended in December 2018, in co-supervision with M. Moakher at ENIT. Current works concern local refinement strategies by splitting algorithms, the arbitrary Lagrangian-Eulerian formulation in the isogeometric context (PhD work of S. Pezzano) and high-order shape sensitivity analysis (Post-doc of M. Stauffert, PRE "GeoSim").

7.5. Sensitivity equation method for hyperbolic systems

Participants: Régis Duvigneau, Camilla Fiorini [UVST], Christophe Chalons [UVST].

While the sensitivity equation method is a common approach for parabolic systems, its use for hyperbolic ones is still tedious, because of the generation of discontinuities in the state solution, yielding Dirac distributions in the sensitivity solution. To overcome this difficulty, we investigate a modified sensitivity equation, that includes an additional source term when the state solution exhibits discontinuities, to avoid the generation of delta-peaks in the sensitivity solution. We consider as typical example the one-dimensional compressible Euler equations. Different approaches are tested to integrate the additional source term: a Roe solver, a Godunov method and a moving cells approach[18].

This study is achieved in collaboration with C. Chalons from University of Versailles, in the context of C. Fiorini's PhD work, defended in July 2018.

7.6. Classification algorithms in Bayesian optimization

Participants: Régis Duvigneau, Matthieu Sacher [Ecole Navale], Frédéric Hauville [Ecole Navale], Olivier Le Maître [CNRS-LIMSI].

A Gaussian-Process based optimization algorithm is proposed to efficiently determine the global optimum for expensive simulations, when some evaluations may fail, due to unrealistic configurations, solver crash, degenerated mesh, etc. The approach is based on coupling the classical Bayesian optimization method with a classification algorithm, to iteratively identify the regions where the probability of failure is high[35].

The method is applied to the optimization of foils and sails in the context of racing yachts[34], in particular for the America's Cup in collaboration with Groupama team. This work was part of M. Sacher's PhD work at Ecole Navale, defended in September 2018.

7.7. Solving with games the coupled problems of conductivity or obstacle identification and data recovery

Participants: Abderrahmane Habbal, Rabeb Chamekh [PhD, LAMSIN, Univ. Tunis Al Manar], Marwa Ouni [PhD, LAMSIN, Univ. Tunis Al Manar], Moez Kallel [LAMSIN, Univ. Tunis Al Manar], Nejib Zemzemi [Inria Bordeaux, EPI CARMEN].

We extend in two directions our previous successful attempts [112], [121] to tackle ill posed inverse problems as Nash games.

In a first direction, a Nash game algorithm is used for the solution of coupled conductivity identification and data completion in cardiac electrophysiology. In [19], we consider the identification problem of the conductivity coefficient for an elliptic operator using an incomplete over-specified measurements on the surface. We define three players with three corresponding criteria. The two first players use Dirichlet and Neumann strategies to solve the completion problem, while the third one uses the conductivity coefficient as strategy, and uses a cost which basically relies on an established identifiability theorem. The implemented algorithm is used for the electrocardiography ECG imaging inverse problem, dealing with inhomogeneities in the torso domain. The inverse problem of ECG consists in finding the electric potential distribution on the heart's surface given the one on the torso, so that it is a data completion problem. Furthermore, in our approach, the conductivity coefficients are known only by an approximate values. we conduct numerical experiments on a 2D torso case including noisy measurements. Results illustrate the ability of our computational approach to tackle the difficult problem of joint identification and data completion.

The second direction deals with Nash strategies for the inverse inclusion Cauchy-Stokes problem. We introduce in [44] a new algorithm to solve the problem of detecting unknown cavities immersed in a stationary viscous fluid, using partial boundary measurements. The considered fluid obeys a steady Stokes regime, the cavities are inclusions and the boundary measurements are a single compatible pair of Dirichlet and Neumann data, available only on a partial accessible part of the whole boundary. This inverse inclusion Cauchy-Stokes problem is ill-posed for both the cavities and missing data reconstructions, and designing stable and efficient algorithms is not straightforward. We reformulate the problem as a three-player Nash game. Thanks to an identifiability result derived for the Cauchy-Stokes inclusion problem, it is enough to set up two Stokes BVP, then use them as state equations. The Nash game is then set between 3 players, the two first targeting the data completion while the third one targets the inclusion detection. We used a level-set approach to get rid of the tricky control dependence of functional spaces, and we provided the third player with the level-set function as strategy, with a cost functional of Kohn-Vogelius type. We propose an original algorithm, which we implemented using Freefem++. We present 2D numerical experiments for three different test-cases.The obtained results corroborate the efficiency of our 3-player Nash game approach to solve parameter or shape identification for Cauchy problems.

7.8. The Kalai-Smorodinski solution for many-objective Bayesian optimization

Participants: Mickael Binois [Univ. Chicago], Victor Picheny [INRA, Toulouse], Abderrahmane Habbal.

Game theory finds nowadays a broad range of applications in engineering and machine learning. However, in a derivative-free, expensive black-box context, very few algorithmic solutions are available to find game equilibria. In [31], we propose a novel Gaussian-process based approach for solving games in this context. We follow a classical Bayesian optimization framework, with sequential sampling decisions based on acquisition functions. Two strategies are proposed, based either on the probability of achieving equilibrium or on the Stepwise Uncertainty Reduction paradigm. Practical and numerical aspects are discussed in order to enhance the scalability and reduce computation time. Our approach is evaluated on several synthetic game problems with varying number of players and decision space dimensions. We show that equilibria can be found reliably for a fraction of the cost (in terms of black-box evaluations) compared to classical, derivative-based algorithms.

Another ongoing scope of research in multi-objective Bayesian optimization is to extend its applicability to a large number of objectives : the so-called many-objective optimization. Regarding the harsh many-objective optimization problems, the recovering of the set of optimal compromise solution generally requires lots of observations while being less interpretable, since this set tends to grow larger with the number of objectives. We thus propose to focus on a choice of a specific solution originating from game theory, the Kalai-Smorodinsky solution, that possesses attractive properties. In particular, it ensures equal marginal gains over all objectives. We further make it insensitive to a monotonic transformation of the objectives by considering the objectives in the copula space. A novel tailored algorithm is proposed to search for the solution, in the form of a Bayesian optimization algorithm: sequential sampling decisions are made based on acquisition functions that derive from an instrumental GP prior. Our approach is tested on three problems with respectively four, six and ten objectives.

The Nash and Kalai-Smorodinsky methods are available in the R package `GPGame` available on CRAN at https://cran.r-project.org/package=GPGame.

7.9. Stochastic multiple gradient descent algorithm

Participants: Jean-Antoine Désidéri, Fabrice Poirion [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.], Quentin Mercier [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.].

We have proposed a new method for multi-objective optimization problems in which the objective functions are expressed as expectations of random functions. The present method is based on an extension of the classical stochastic gradient algorithm and a deterministic multi-objective algorithm, the Multiple Gradient Descent Algorithm (MGDA). In MGDA a descent direction common to all specified objective functions is identified through a result of convex geometry. The use of this common descent vector and the Pareto stationarity definition into the stochastic gradient algorithm makes the algorithm able to solve multi-objective problems. The mean square and almost sure convergence of this new algorithm are proven considering the classical stochastic gradient algorithm hypothesis. The algorithm efficiency is illustrated on a set of benchmarks with diverse complexity and assessed in comparison with two classical algorithms (NSGA-II, DMS) coupled with a Monte Carlo expectation estimator [129]

7.10. Non-convex multiobjective optimization under uncertainty

Participants: Jean-Antoine Désidéri, Fabrice Poirion [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.], Quentin Mercier [ONERA Châtillon, Aeroelasticity and Structural Dynamics Dept.].

A novel algorithm for solving multi-objective design optimization problems with non-smooth objective functions and uncertain parameters is presented. The algorithm is based on the existence of a common descent vector for each sample of the random objective functions and on an extension of the stochastic gradient algorithm. The proposed algorithm is applied to the optimal design of sandwich material. Comparisons with the genetic algorithm NSGA-II and the DMS solver are given and show that it is numerically more efficient due to the fact that it does not necessitate the objective function expectation evaluation. It can moreover be entirely parallelized. Another simple illustration highlights its potential for solving general reliability problems, replacing each probability constraint by a new objective written in terms of an expectation. Moreover, for this last application, the proposed algorithm does not necessitate the computation of the (small) probability of failure [129].

8. Partnerships and Cooperations

8.1. European Initiatives

8.1.1. FK32

Title: Multi-agent Fokker-Planck Nash games

Programm: Bayerisch-Französische Hochschulzentrum / Centre de Coopération Univ. Franco-Bavarois (BFHZ-CCUFB)

Duration: January - December 2018

PIs: A. Borzi (Univ. Wuerzburg) and A. Habbal

The purpose of this project is the formulation and application of a new mathematical framework for modeling avoidance and/or meeting in multi-agents' motion in the framework of differential games with stochastic processes and related Fokker-Planck equations.

8.1.2. FP7 & H2020 Projects

8.1.2.1. TramOpt

Title: A Traffic Management Optimization platform for enhanced road network efficiency

Programm: H2020

Duration: Mai 2017 - Octobre 2018

Coordinator: Inria

Inria contact: Paola Goatin

Building on the advances of the ERC TRAM3 project, the TRAMOPT PoC project aims are twofold:

- developing a robust prototype to allow real-life testing and deployment of a novel traffic control Decision Support System (DSS) based on a software platform for road traffic management including variable speed limits, ramp-metering and re-routing policies. This DSS is intended for public and private traffic managers to increase freeway network performances (e.g. congestion and pollution reduction);
- assessing the exploitation perspectives through a dedicated market study evaluating the added value of TRAMOPT over existing solutions and identifying the best business approach to foster uptake and commercialization of our technology.

8.2. International Initiatives

8.2.1. NAMReD

Program: Program Hubert Curien PHC Utique (Tunisia)

Project acronym: NAMReD

Project title: Novel Algorithms and Models for Data Reconstruction

Duration: January 2018 - December 2020

Coordinator: A. Habbal and M. Kallel (Univ. Tunis al Manar)

Abstract: The project goal is the design of new and efficient algorithms tailored for data reconstruction involving ill-posed problems. We rely on an original use of game theory and p-Kirchhoff methods. We apply these approaches for missing data recovery and image restoration.

8.2.2. Inria International Labs

Inria Chile

Associate Team involved in the International Lab:

8.2.2.1. NOLOCO

Title: Efficient numerical schemes for non-local transport phenomena

International Partner (Institution - Laboratory - Researcher):

Universidad del Bio-Bio (Chile) - Department of Mathematics - Luis Miguel Villada Osorio

Start year: 2018

See also: https://team.inria.fr/acumes/assoc-team/noloco/

This project tackles theoretical and numerical issues arising in the mathematical study of conservation laws with non-local flux functions. These equations include in a variety of applications, ranging from traffic flows to industrial processes and biology, and are intended to model macroscopically the action of non-local interactions occurring at the microscopic level.

The team, bi-located in France and Chile, has complementary skills covering the analysis, numerical approximation and optimization of non-linear hyperbolic systems of conservation laws, and their application to the modeling of vehicular and pedestrian traffic flows, sedimentation and other industrial problems.

Based on the members' expertise and on the preliminary results obtained by the team, the project will focus on the following aspects: - The development of efficient, high-order finite volume numerical schemes for the computation of approximate solutions of non-local equations. - The sensitivity analysis of the solutions on model parameters or initial conditions

The impact of the project is therefore twofold: while addressing major mathematical advances in the theory and numerical approximation of highly non-standard problems, it puts the basis for innovative tools to handle modern applications in engineering sciences.

8.2.3. Inria International Partners

8.2.3.1. ORESTE

Title: Optimal REroute Strategies for Traffic managEment

International Partner (Institution - Laboratory - Researcher):

University of California Berkeley (United States) - Electrical Engineering and Computer Science (EECS) (EECS) - Alexandre M. Bayen

Duration: 2018 - 2022

Start year: 2018

See also: https://team.inria.fr/acumes/assoc-team/oreste

The rapidly changing transportation ecosystem opens new challenges in traffic modeling and optimization approaches. We will focus in particular on the two following aspects:

Route choice apps impact. The vast use of personal route choice systems through phone applications or other devices is modifying the traditional flow of networks, requiring new models for accounting of the guidance impact. Indeed, routing apps have changed traffic patterns in the US and Europe, leading to new congestion patterns where previously no traffic was observed. Over the last decade, GPS enabled smart phones and connected personal navigation devices have disrupted the mobility landscape. Initially, the availability of traffic information led to better guidance of a small portion of motorists in the system. But as the majority of the driving public started to use apps, the systematic broadcasting of "selfish" best routes led to the worsening of traffic in numerous places, ultimately leading to the first lawsuit against one specific company in particular (Waze) accused to be the cause of these problems. This is just the beginning of an evolution, which, if not controlled and regulated, will progressively asphyxiate urban landscapes (already nearly hundreds of occurrences of this phenomenon are noticed by the popular media, which indicates the presence of probably thousands of such issues in the US alone). Traffic managers are typically not equipped to fix these problems, and typically do not fund this research, as in order to be able to regulate and fix the problem, fundamental science needs to be advanced, modeling and game theory in particular, so remediation can happen (for which the traffic managers are equipped). In this project, we will mainly focus on the development and study of new macroscopic dynamical models to describe the aforementioned phenomena, and we will explore control strategies to mitigate their impact.

Autonomous vehicles. Besides, the foreseen deployment of connected and autonomous vehicles (CAVs) opens new perspectives both in traffic modeling and control. Indeed, CAVs are expected to modify the classical macroscopic traffic dynamics due to their peculiar motion laws, which are more uniform than human drivers' and follow different rules. Besides, due to their extended information on neighboring traffic conditions, the resulting dynamics would have a non-local character, justifying the use of rapidly developing non-local models. In any case, the different behavior of autonomous vehicles requires the design of new multi-class models capable of accounting for different vehicle classes characteristics and mutual interactions. Moreover, CAVs could be used as endogenous variable speed limiters, thus providing new action points to control traffic flow. Preliminary results show that the presence of few controlled vehicles can positively affect traffic conditions. In this setting, the interaction of AVs with the surrounding traffic can be described by strongly coupled PDE-ODE systems, which have been largely studied by the ACUMES team. Yet, the study of CAVs impact in realistic situations requires further research, in particular towards model validation, for which the Berkeley team will provide the necessary data.

8.2.3.2. Informal International Partners

University of Brescia, Information Engineering (R.M. Colombo: http://rinaldo.unibs.it/)

University of Mannheim, Scientific Computing Research Group (SCICOM) (S. Göttlich: http://lpwima.math.uni-mannheim.de/de/team/prof-dr-simone-goettlich/)

University of Rutgers - Camden, Department of Mathematical Science (B. Piccoli: https://piccoli.camden.rutgers.edu/)

University of Texas Arlington (S. Roy, https://mentis.uta.edu/explore/profile/souvik-roy)

Technical University of Kaiserslautern - Department of mathematics (B. Simeon https://www.mathematik.uni-kl.de/en/das/people/head/simeon/)

8.3. International Research Visitors

8.3.1. Visits of International Scientists

- M.D. Rosini (January 2018, Lublin University): co-direction of N. Dymski's PhD thesis.
- R.M. Colombo (July 2018, Brescia University): well-posedness of Initial Boundary Value Problems.
- L.M. Villada (September 2018, University of Bio-Bio): finite volume schemes for non-local systems of conservation laws.

8.3.2. Visits to International Teams

8.3.2.1. Research Stays Abroad

- N. Laurent-Brouty visited UC Berkeley (A. Bayen) for 1 month in April-May 2018.
- E. Rossi visited Mannheim University (S. Göttlich) for 1.5 months in September-October 2018.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

9.1.1.1. General Chair, Scientific Chair

- P. Goatin is member of the the scientific committee of the annual seminar CEA-GAMNI *"Numerical fluid-mechanics"*.
- P. Goatin was member of the scientific committee of *"HYP2018 - Conference on Hyperbolic Problems: Theory, Numerics, and Applications"*, Penn State (USA), June 2018.
- P. Goatin was member of the scientific committee of *"PED2018 - Conference on Pedestrian and Evacuation Dynamics"*, Lund (Sweden), August 2018.

9.1.1.2. Member of the Organizing Committees

- P. Goatin and M.L. Delle Monache (Inria Grenoble) organized the mini-symposium *"Modélisation et gestion du trafic routier"*, CANUM 2018 - 44e Congrès National d'Analyse Numérique, Cap d'Agde (France), May 2018.
- P. Goatin and J. Pettré (Inria Rennes) organized the workshop *"Modélisation du piéton et de la foule en mouvement"*, Saclay (France), November 2018.
- P. Goatin was member of the organizing committee of the workshop *"Mathematical modeling with measures: where applications, probability and determinism meet"*, Lorentz Center, Leiden (The Netherlands), December 2018.
- R. Duvigneau and A. Habbal are members of the OC for the FGS French-German-Swiss Conference on Optimization, Nice, September 2019.

9.1.2. Scientific Events Selection

9.1.2.1. Member of the Conference Program Committees

- A. Habbal was PC member of the African Conference on Research in Computer Science and Applied Mathematics (CARI 2018), Stellenbosch, South Africa
- P. Goatin was member of the International Program Committee of *"CTS2018 - 15th IFAC Symposium on Control in Transportation Systems"*, Savona (Italy), June 2018.

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- P. Goatin is Managing Editor of *Networks and Heterogeneous Media*.

9.1.3.2. Reviewer - Reviewing Activities

- J.-A. Désidéri has made reviews for *Mathematical Problems in Engineering* (Hindawi Publishing Corporation) and *Numerical Algorithms* (Springer),
- R. Duvigneau is a reviewer for the following international journals : Computers & Fluids, International Journal for Numerical Methods in Fluids, Computer Methods for Applied Mechanical Engineering, Computer Aided Geometric Design, Applied Mathematics & Mechanics, Engineering Optimization.
- P. Goatin reviewed for the following international journals: SIAM Journal of Applied Mathematics; Networks and Heterogeneous Media; European Journal of Applied Mathematics; Journal of Advanced Transportation; IEEE Transactions on Intelligent Transportation Systems; Discrete and Continuous Dynamical Systems A.
- A. Habbal is reviewer for the following international journals: Journal of Structural and Multidisciplinary Optimization ; Journal of Math. Model. Nat. Phenom. ; Int. Journal of Mathematical Modeling and Numerical Optimization; Journal of Differential Equations; American Mathematical Society Reviews; European Journal of Operation Research (EJOR); Journal of Optimization Theory and Algorithms (JOTA).

9.1.4. Invited Talks

- F.A. Chiarello: Interactive workshop on hyperbolic equations, University of Ferrara (Italy), September 2018.
  Invited talk: *"Non-local multi-class traffic flow models"*.
- J.-A. Désidéri: Prioritized Multiobjective Optimization Using Nash Games - Towards Adaptive Optimization, ONERA, Toulouse, December 20, 2018.
- P. Goatin: ECMI 2018 - 20th European Conference on Mathematics for Industry, Budapest (Hungary), June 2018.
  Plenary talk: *"Traffic management by macroscopic models"*.

- P. Goatin: 14th Franco-Romanian Conference on Applied Mathematics, Bordeaux (France), August 2018.
  Plenary talk: *"Traffic management by macroscopic models"*.
- P. Goatin: Rencontres Normandes sur les aspects théoriques et numériques des EDP, Rouen (France), November 2018.
  Invited talk: *"Conservation laws with local constraints arising in traffic modeling"*.
- P. Goatin: LIA COPDESC Workshop "Analysis, control and inverse problems for PDEs", Napoli (Italy), November 2018.
  Plenary talk: *"Traffic control by autonomous vehicles"*.
- P. Goatin: CDC 2018 - 57th IEEE Conference on Decision and Control, Miami, FL (USA), December 2018. Workshop "Traffic Flow Control via PDE Techniques".
  Invited talk: *"Macroscopic modeling of traffic control by autonomous vehicles"*.
- A. Habbal: XI NPU-UTC Sino-French Seminar on Mechanics and Design of Advanced Material and Structures Symposium, Xi'An, China, April 2018.
  Plenary talk: *Games to solve Joint Data Completion and Obstacle Detection in Stokes Problems*.
- A. Habbal: Univ. Wurzburg Chair of Mathematics (Scientific Computing) Mathematical Colloquium, Wurzburg, May 2018.
  Plenary talk: *Games to solve Joint Data Completion and Obstacle Detection in Stokes Problems*.
- A. Habbal: Conference on Inverse Problems, Control and Shape Optimization (PICOF) Beirut, Lebanon, June 18-20 2018.
  Invited talk: *Detection of inclusions while recovering boundary data in Stokes Flows using Nash strategies*.
- A. Habbal: University Mohamed V, Rabat, June 2018.
  Plenary talk: *Avoidance mechanisms arising as Nash equilibria in Fokker-Planck constrained games*.
- E. Rossi: IFIP TC 7 Conference on System Modelling and Optimization, Essen (Germany), July 2018. Workshop "Modeling and optimization of networked systems".
  Invited talk: *"Crowd dynamics in domains with boundaries"*.

9.1.5. Scientific Expertise

- P. Goatin was proposals reviewer for FONDECYT program of CONICYT (National Committee of Science and Technology Research, Chile), 2018.

9.1.6. Research Administration

- P. Goatin is member of the board of the Doctoral School of Fundamental and Applied Sciences (ED SFA) of Université Côte D'Azur.
- P. Goatin was member of BCP ("Bureau du Comité des Projets") at Inria Sophia Antipolis Méditerranée (until August 2018).
- P. Goatin was member of the admission committee for Inria 2018 competitive selection of senior researchers (DR2).
- R. Duvigneau is member of CSD ("Comité Suivi Doctoral) at Inria Sophia Antipolis Méditerranée.
- R. Duvigneau is responsible for the Immersive Space Committee at Inria Sophia Antipolis Méditerranée.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Master: Advanced Optimization, 40.5 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (J.-A. Désidéri, R. Duvigneau).

Master: Conservation laws and finite volume scheme, 30 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (P. Goatin).

Master: Multidisciplinary Optimization, 22.5 hrs, joint *Institut Supérieur de l'Aéronautique et de l'Espace* (ISAE Supaéro, "Complex Systems") and M2 (Mathematics), Toulouse (J.-A. Désidéri).

Licence: Summer Project in Mathematical Modeling, 36 hrs, L3, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Numerical Methods for Partial Differential Equations, 66 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal and R. Duvigneau).

Master: Optimization, 66 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Modeling strategies for e-Formula races, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Multi-agents Systems, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Modeling and simulation of electric mobility, 10 hrs, M1 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Licence (L3): Implement and Experiment PSO, 48hrs, L3 Semester Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Graduate autumn school "Theoretical and numerical aspects of PDEs", Rouen (France), November 2018. Lecture: *"Macroscopic traffic flow models on networks"* (P. Goatin).

9.2.2. Supervision

PhD in progress: Rabeb Chamekh, *Game strategies for thermo-elasticity*, Jan 2015, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis)

PhD in progress: Marwa Ouni, *Solving inverses problems in fluid mechanics with game strategies*, October 2016, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis)

PhD in progress: Kelthoum Chahour, *Modeling and optimal design of coronary angioplastic stents*, Nov 2015, Supervisors: A. Habbal, Rajae Aboulaich (LERMA, EMI, Rabat)

PhD defended in June 2018: C. Durantin, *Métamodélisation et optimisation de dispositifs photoniques* (Meta-modelling and Optimization for nanophotonic devices), University of Nice - Sophia Antipolis, June 2018. Supervisors: J.-A. Désidéri and A. Glière (CEA LETI).

PhD defended in October 2018: Q. Mercier, *Algorithme de descente pour la résolution de problèmes d'optimisation multiobjectif sous incertitudes* (Descent Algorithm for the solution of multi-objective optimization problems under uncertainties), University of Nice - Sophia Antipolis, October 2018. Supervisors: J.-A. Désidéri and F. Poirion (ONERA Châtillon).

PhD defended in December 2018: A. Azaouzi, *isogeometric analysis methods for hyperbolic systems*, ENIT (Tunisia) / University of Nice - Sophia Antipolis, Oct. 2018. Supervisors: R. Duvigneau and M. Moakher (ENIT).

PhD defended in November 2018 : Sosina Mengistu-Gashaw (EURECOM), *Mobility and connectivity modelling of 2-wheels traffic for ITS applications* , March 2015. Supervisors: P. Goatin and J. Härri (EURECOM).

PhD defended in September 2018: M. Sacher, *advanced methods for numerical optimization of yacht performance*, Ecole Navale , Oct. 2014. Supervisors: R. Duvigneau, O. Le Maitre (LIMSI), F. Hauville and J.-A. Astolfi (Ecole Navale).

PhD defended in July 2018: C. Fiorini, *Sensitivity equation method for hyperbolic systems*, Univ. Versailles, Oct. 2014. Supervisors: R. Duvigneau, C. Chalons (Univ. Versailles).

PhD in progress: S. Pezzano, *Isogeometric analysis with moving grids*, Univ. Nice Sophia-Antipolis. Supervisor: R. Duvigneau.

PhD in progress : Nicolas Laurent-Brouty (ENPC), *Macroscopic traffic flow models for pollution estimation and control*, September 2016. Supervisor: P. Goatin.

PhD in progress : Felisia Angela Chiarello (Université de Nice Sophia Antipolis), *Conservation laws with non- local flux*, October 2016. Supervisor: P. Goatin .

PhD in progress : Nikodem Dymski (Maria Curie Sklodowska University & Université de Nice Sophia Antipolis), *Conservation laws in the modeling of collective phenomena*, October 2016. Supervisors: P. Goatin and M.D. Rosini (UMCS).

9.2.3. Juries

- R. Duvigneau was member of the committee of P. Ploe's PhD thesis *"Surrogate based optimization of hydrofoil shapes using RANS simulations"*, Ecole Centrale de Nantes, June 26th, 2018.
- R. Duvigneau was member of the committee of F. Mastrippolito's PhD thesis *"Optimisation de forme numérique de problèmes multiphysiques et multiéchelles : application aux échangeurs de chaleur"*, Ecole Centrale de Lyon, December 14th, 2018.
- P. Goatin was referee of M. Pfirsching's PhD thesis *"A multi-scale model for material flow problems based on a non-local conservation law: simulation and optimization"*, Universität Mannheim, April 11th, 2018.
- J.-A. Désidéri was referee of T. Achard's PhD. Thesis *Techniques de calcul du gradient aéro-structure haute-fidélité pour l'optimisation de voilures flexibles* (Techniques for computing the high-fidelity aero-structural gradient for the optimization of flexible wings), CNAM, Paris, December 2017.
- J.-A. Désidéri was a member of the jury of J. Mas Colomer's Phd. Thesis *Similitude Aéroélastique d'un Démonstrateur en Vol via l'Optimisation Multidisciplinaire* (Aeroelastic similarity of a Flight Demonstrator via Multidisciplinary Optimization), University of Toulouse, December 2018.

9.3. Popularization

9.3.1. Articles and contents

- Press article: *Dossier. Cette mathématicienne met le trafic en équation pour réduire les embouteillages*, Nice Matin, August 2018 (P. Goatin).
- TV interview for the program "Dimanche en politique", France 3 Côte d'Azur channel, October 14, 2018 (P. Goatin).

10. Bibliography

Major publications by the team in recent years

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[17] K. CHAHOUR, R. ABOULAICH, A. HABBAL, C. ABDELKHIRANE, N. ZEMZEMI. *Numerical simulation of the fractional flow reserve (FFR)*, in "Mathematical Modelling of Natural Phenomena", 2018, https://hal.inria.fr/hal-01944566

[18] C. CHALONS, R. DUVIGNEAU, C. FIORINI. *Sensitivity analysis and numerical diffusion effects for hyperbolic PDE systems with discontinuous solutions. The case of barotropic Euler equations in Lagrangian coordinates*, in "SIAM Journal on Scientific Computing", November 2018, vol. 40, n° 6, pp. A3955-A3981, https://hal.inria.fr/hal-01589337

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